# CALORIMETRY OPTIMISED FOR JETS

HENRI VIDEAU, JEAN-CLAUDE BRIENT

*Laboratoire Leprince-Ringuet Ecole polytechnique - F-91128 Palaiseau, France*
*E-mail: Henri.Videau@in2p3.fr*

The physics programme for a coming electron linear collider is dominated by events with final states containing many jets, dijets from H, W, Z . We contend that, in the energy range under consideration, the best approach is to optimise the independent measurement of the tracks in the tracker, the photons in the electromagnetic calorimeter and the neutral hadrons in the calorimetry, together with a good lepton identification. This can be achieved with a good tracker and a high granularity calorimetry providing particle separation, through an efficient energy flow algorithm. But we do not contend that this is a universal panacea. Following that programme from the calorimetric side on hardware and software issues is the goal of the CALICE collaboration.

In this paper we will discuss four topics, one deals directly with reconstructing jet energies in the energy range of the linear collider, the second presents a possible implementation of a calorimeter for that purpose (namely one TESLA TDR implementation), the third presents current results on reconstruction and specifically on photon reconstruction, the last gives some status of the developments going on in the CALICE collaboration for a digital hadron calorimeter hardware.

## 1. Measuring the energy of jets, the requirements

### 1.1. *The physics*

The coming linear collider will cover an energy range from the Z mass to the TeV. Among the subjects of interest, aside the top production, the Higgs production in $e^+e^- \to ZH$, the Higgs self-coupling $e^+e^- \to ZHH$, the production of bosons $e^+e^- \to W^+W^-$, $e^+e^- \to WW\nu\bar{\nu}$ or $e^+e^- \to ZZ\nu\bar{\nu}$, not to speak about supersymmetric channels. To extract at best all the physics we will have to manage the multijet (dijets) events and to identify and measure well the leptons, electrons and muons but also the taus which are slightly more challenging.

It may be of interest to have a glance at the object of our study. How do these jets look like. This can be seen in figure 1.

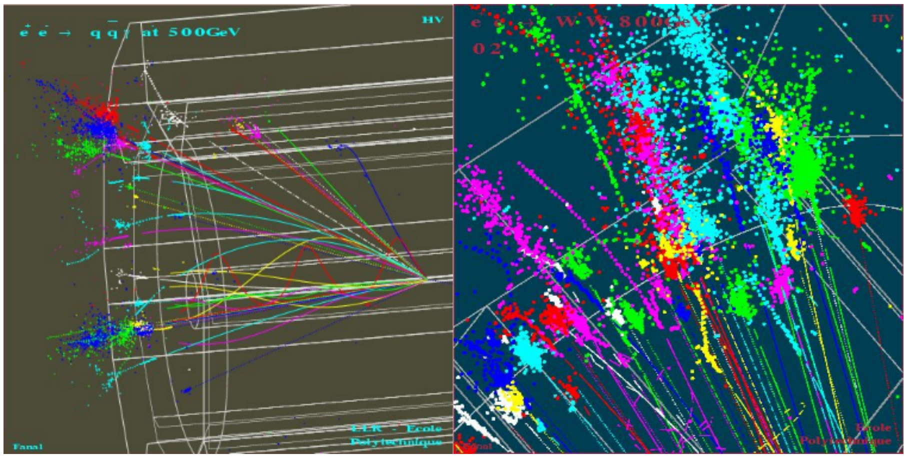


Figure 1. Having a look at jets, on the left a radiative $q\bar{q}$ at 500 GeV, on the right a W from $e^+e^- \to WW$ at 800 GeV.

On the left image you see a $q\bar{q}$ at 500 GeV, in a frequent configuration with a large radiative photon leaving to the right. The two jets with a Z mass are strongly boosted toward the end cap. On the right a W from $e^+e^- \to WW$ at 800 GeV is also boosted toward the end cap due to the t-channel exchange process. The direction of the view optimises the separation of the dijet particles.

The approach we consider to reconstruct the jets is called the "analytical energy flow method" (AEF). It has been used extensively at LEP in particular by ALEPH. An illustration of the ALEPH detector behaviour is shown on figure 2. This is a peculiar tau event where the tau decays through $\tau \to \nu_\tau \pi K_s K_l$. The $K_l$ is easily seen in the HCAL, the pattern is obtained by the streamer tubes parallel to the beam and read digitally, the energy can be measured using analog signals from cathode towers or counting the tubes. The LEP example is relevant because, the multiplicity increasing, the energy spectrum of the different particles is quite similar at LEP and at the higher energies of the linear collider.

But other lessons can be learned from the LEP detectors: if you want to properly measure the neutral hadron energy it is particularly nasty to insert a thick coil in front of the HCAL, empty projective cracks should be avoided in ECAL and HCAL, the longitudinal segmentation has to be good enough, and, if the ALEPH tau shows the interest of the digital pattern, to make use of the pattern in more complex events a 3d read-out is mandatory.

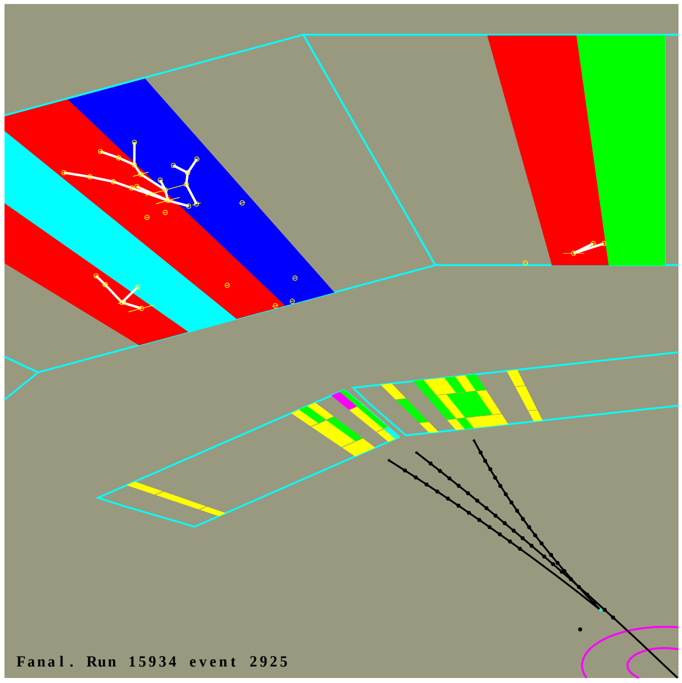



Figure 2. A remarquable tau decay seen in ALEPH: $\tau \to \nu_\tau \pi K_s K_l$. The $K_l$ is seen as a pattern in the HCAL and an imbalance in the energies.

### 1.2. *Impact on the physics programme of the jet resolution*

The first argument in favour of the effort to ameliorate the jet resolution is in the impact a given resolution has on specific studies. Only few channels have been up to now studied and this is a place where more work is absolutely needed. To quantify, the resolution has been parametrised in a very classical way as $\Delta E = \alpha/\sqrt{E}$. The absence of a constant term may seem inadequate, but the value we use in the most favourable case ($\alpha = 0.3$) has been obtained with that formula in a simulation study of jets at the Z.

For $e^+e^- \to ZHH$ it has been shown that, for a luminosity of 1 ab$^{-1}$, going from $\alpha = 0.6$ to 0.3 improves the significance of the observation of the signal from 3 to 6 $\sigma$, the difference between a hint and a discovery. For $e^+e^- \to ZH$ where $Z \to q\bar{q}$ and $H \to WW^*$ going from 0.3 to 0.6 is equivalent to loosing 45 % of the luminosity. A visual evidence is shown on figure 3. The reactions $e^+e^- \to WW\nu\bar{\nu}$ and $e^+e^- \to ZZ\nu\bar{\nu}$ have been simulated in the TESLA detector through a fast simulation taking properly into account the imperfections of the detector, we can remark that the typical energy of the jets making the W's is not dramatically different from the energy of a jet at the Z peak and then not introducing a constant term has little effect. The separation between WW and ZZ is clear on these scatter plots for 0.3 and purely statistical for 0.6. This can be quantified as an equivalent loss of luminosity of 40%. Thus the price of a more elaborate calorimeter is to be compared with the corresponding additional running cost.

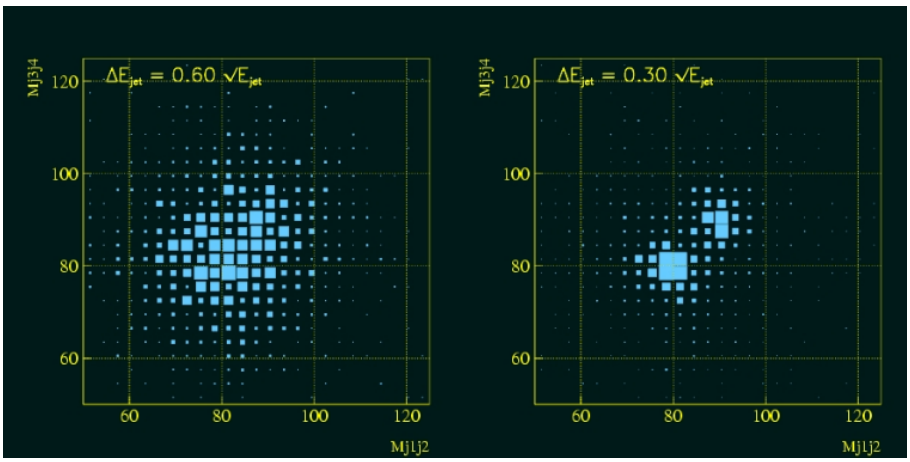



Figure 3. Separation between $e^+e^- \to WW\nu\bar{\nu}$ and $e^+e^- \to ZZ\nu\bar{\nu}$ for a jet resolution of $0.3/\sqrt{E}$.

### 1.3. *Reminder of the basics of the analytical energy flow method*

The first point is to remember that we want both to measure well the jets and properly identify the leptons even inside jets. The fact that muon energy can not be measured by calorimetry as well as the distorsion introduced in a global calorimetric energy flow by the action of the strong field on charged particles are, aside the resolution obtained, the arguments for an analytic energy flow rather than a purely calorimetric one. The presence of a lepton in a jet is the signature of a neutrino, even signing taus in jets may be worthwhile. The energy flow of a jet is written as the sum of its components: $P_{jet} = \sum P_{chargedparticles} + \sum P_\gamma + \sum P_{neutralhadrons}$, The basic argument then goes as follows: the charged particles make about 60% of the energy and, being of rather low energy, are much better measured by the tracker, the goal is just to isolate the 10% neutral hadron energy. Such a method relies much more on the separation of particles than on the calorimeter intrinsic energy resolution.

The basic requirements for a calorimeter design are easy to derive. The calorimeter has to be far enough from the interaction point, entirely inside a coil providing a strong field to widen the jets, it has to be compact with a small radiation length, a small interaction length but large compared to the radiation length in the first part dedicated to the measurement of photons and electrons. Then the read out has to have a granularity matched to the radiation length plus the capability to follow minimum ionising particles as a tracker.

We need a good tracker, not so much on momentum resolution but with good track efficiency, small rate of fake energetic tracks, good $V^0$ identification and small rate of reinteraction. We need a good electromagnetic calorimeter, not so much on resolution but with good photon efficiency, even close to hadrons, a small rate of fakes from hadronic debris, a good electron identification (prompt electrons, this is a requirement for the tracker). We need a good hadron calorimeter to identify muons in particular at energies where they do not reach the muon system, to disentangle neutral hadronic showers from charged ones in order to measure their energy.

## 2. Elements for a calorimetric design (from the TESLA TDR)

Few words to recall the calorimeter design as seen in the TESLA TDR. The electromagnetic part of the calorimeter is made of a sandwich of tungsten radiator and silicon diodes detector. A total depth of 24 $X^0$ in 40 layers provides a resolution around $0.11/\sqrt{E}$ for a total thickness of 20cm. The way to dispose the modules in an eightfold way (figure 4) eliminates the cracks between modules. The cell size matched to the mean Molière radius is about 1cm$^2$. The efficiency to minimum ionising particles is obtained by a mips to noise ratio of about 10.

The hadronic part has a radiator adapted to the optimisation between intrinsic resolution and separation. This is illustrated in figure 5 where a jet is shown developping in an iron structure and in a mixture incorporating tungsten. In the second version the electromagnetic subshowers are kept much smaller inducing a loss in resolution but better separation. The cells are kept very small 1cm$^2$ but this granularity is payed by a yes/no (digital) read out. In fact we will see in the following section that we do not loose anything. In the CALICE collaboration another HCAL solution using scintillator tiles with an analog read out is being studied as well. Note that the cracks between modules are kept projective, but they are very small compared to a shower and for muons which would escape detection, it is evident that a particle going through iron without any interaction is a muon.

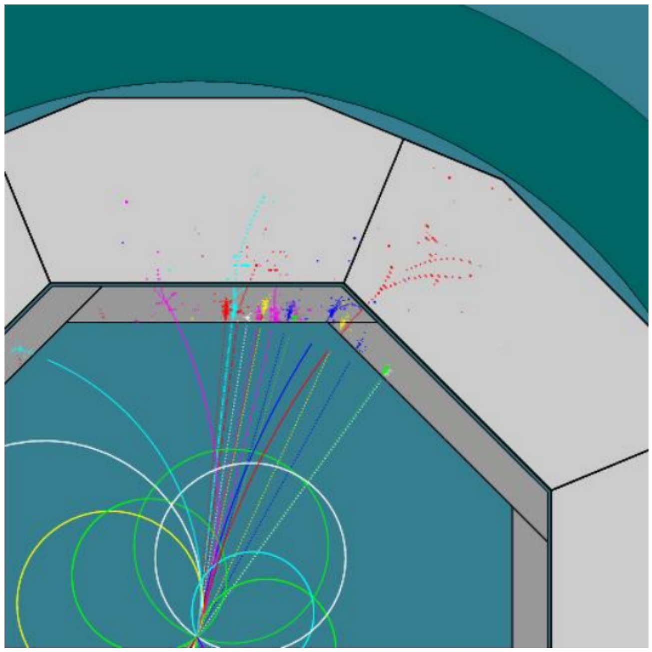


Figure 4. A view of the barrel calorimeter showing the eightfold structure.

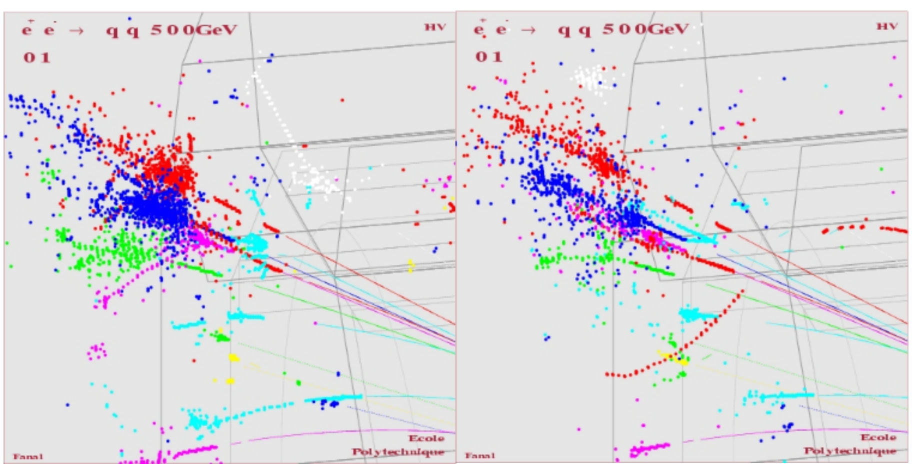



Figure 5. Where it appears that, even for a same mean interaction length, stainless steel and wolfram do not produce similar showers.

## 3. Some results about reconstruction

The calorimeter design requirements have to be validated by a full simulation. In the following studies the simulation used is MOKKA, an application developped on GEANT4.

We first consider some results presented in the TDR. For that purpose the HCAL was simulated with an iron radiator and scintillator cells 1 cm$^2$. The resolution for single particles obtained by summing the energy and by counting the hits is shown on figure 6. It can be seen that the resolution by counting is better. This, which may appear surprising at first sight, is due to the fact that simply counting reduces some of the shower fluctuations. The draw back is that it will eventually introduce a non linearity with energy; but this happens, with that particular design, only at energy well above the interesting range. The use of a neural network to estimate the energy from the digital hits provides also some improvement.

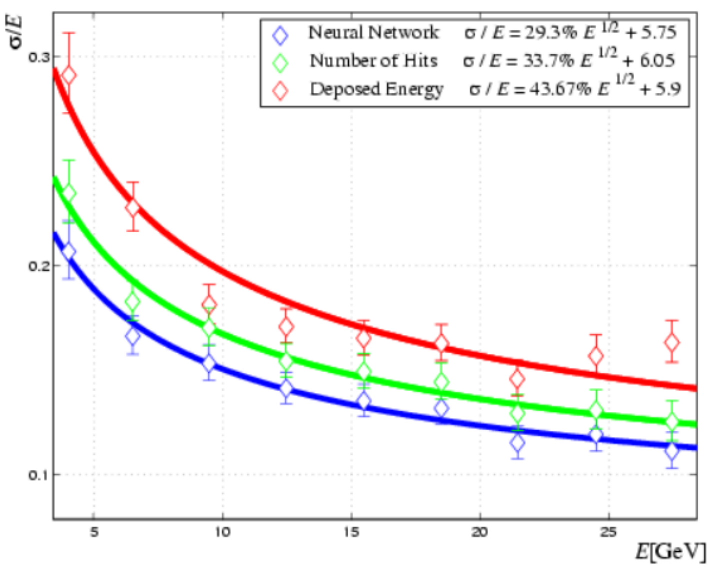



Figure 6. Resolution observed in measuring the deposited energy or the number of cells. For the last solution a neural net improves quite a lot.

The figure 7 shows the energy resolution for $q\bar{q}$ at the Z mass obtained using a neural net. It is roughly interpreted as a $0.3/\sqrt{E}$ resolution.

Can these performances be kept at high energies for narrow jets like seen on figure 8? The jet energies are obtained in a multi step process. Knowing the extrapolation of the charged tracks, reconstruct the photons in the Ecal, subtract the cells of these photons, identify the hadrons, estimate the energy of the neutral hadrons, possibly with a neural net. In fact different methods are being studied, with neural nets obviously, but also with thermodynamical

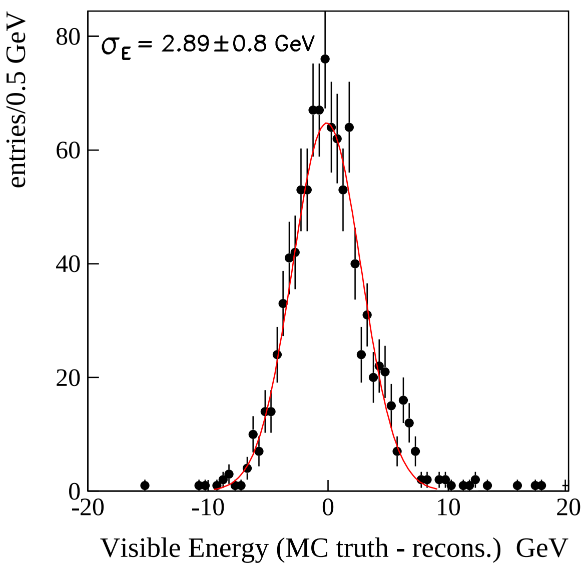



Figure 7. Resolution as the difference between the Monte Carlo truth and the reconstructed energy for jets at the Z mass.

models for example.

A proper reconstruction is the cornerstone of jet calorimetry.

In the following figures some results on photon reconstruction at the highest energies are shown, specifically from $e^+e^- \to WW$ at 800 GeV. They have been obtained with REPLIC a code you can find on the CALICE web site. First we discuss the information on an event by event basis, then on a photon by photon basis.

The figure 9 shows the comparison between reconstructed and generated photon multiplicity in an event. On the left a scatter plot shows that the number of fake photons equals quite well the number of lost photons. Their energy distribution is shown on the right. A similar information regarding the energy is shown on figure 10. It is clear that the total amount of photon energy in an event is properly obtained.

On a photon by photon basis, the figure 11 shows the energy spectra for generated and reconstructed photons. The agreement is good in general but an excess of reconstructed photons appears below 500 MeV. These are fakes from hadronic debris. The figure 12 shows a similar distribution but the "true" photons only have been kept. It measures the efficiency which drops strongly below 250 MeV. The way to assess the fact that a reconstructed photon is a true photon is by requiring that more than 75 % of its energy comes from

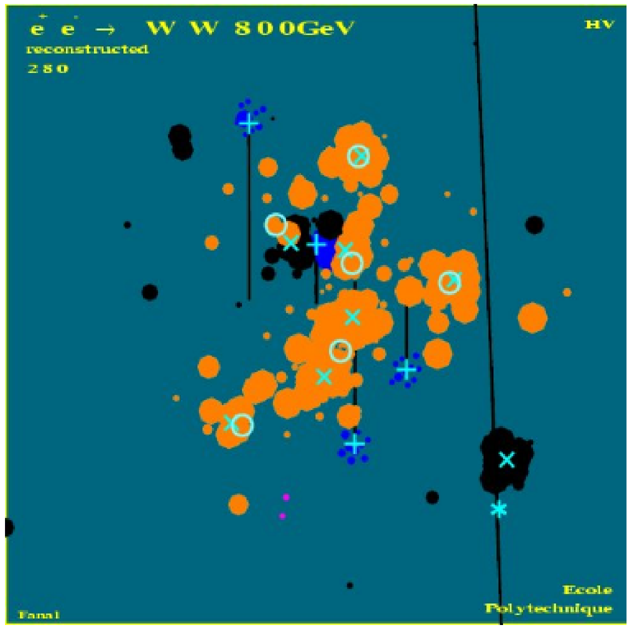



Figure 8. Looking at the impact of a W dijet from $e^+e^- \to WW$ on the first 4 $X^0$ of the electromagnetic calorimeter. This is a $\theta - \phi$ view, the size of the image is 100 mrad. The crosses are the generated photon impacts (8), the pluses the imapct of the charged tracks (4), the stars those of the neutral hadrons (1), the circles are the reconstructed photons.

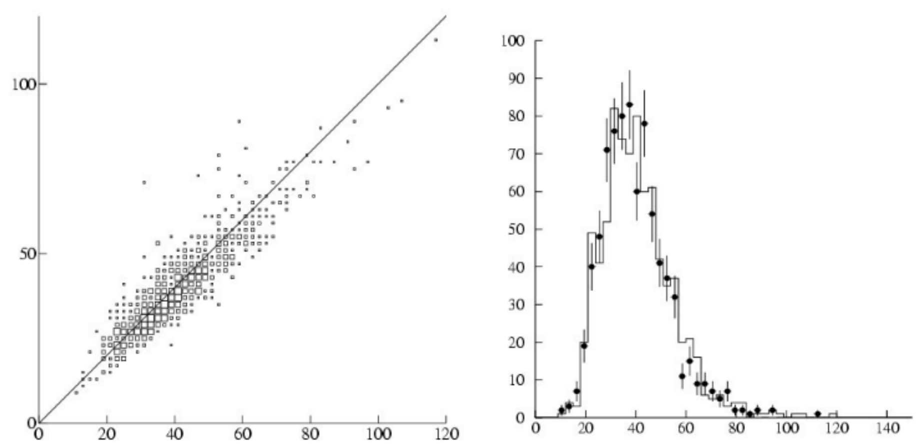


Figure 9. Photon multiplicity per event reconstructed versus generated.

a generated photon. The efficiency can then be derived and is presented for the low energy part in figure 13. Above 2 GeV it is essentially 1. Finally

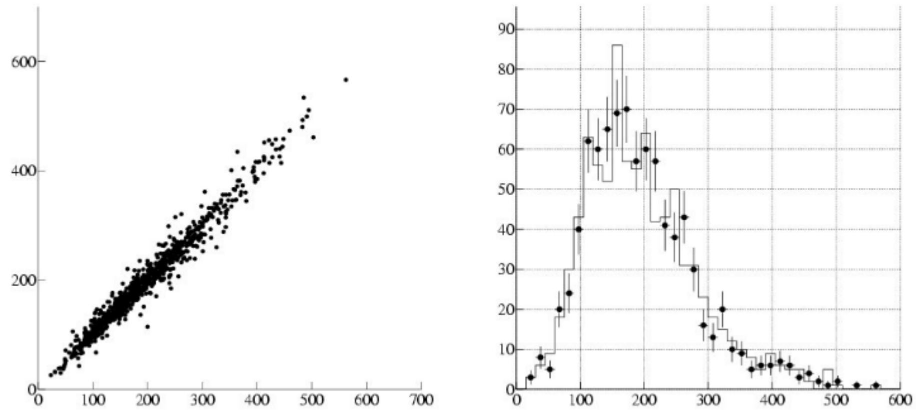



Figure 10. Photon energy per event reconstructed versus generated.

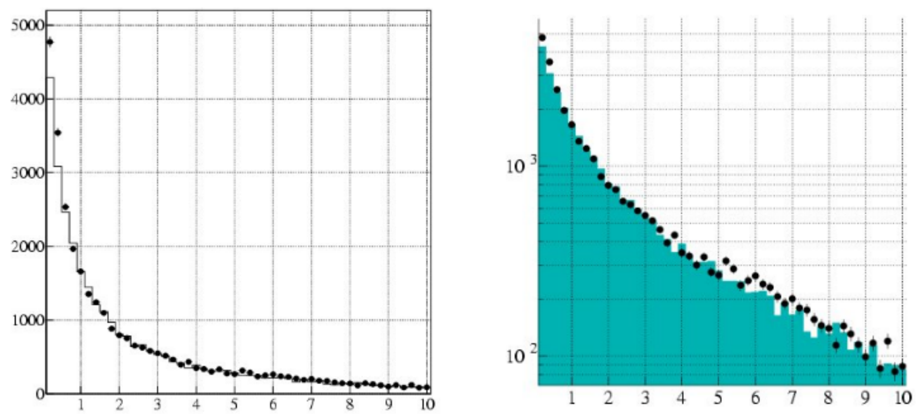



Figure 11. Photon energy distribution, generated (histogram) and reconstructed (points), the left figure is in linear scale, the right one in log scale.

the energy resolution for the photon contribution in $e^+e^- \to WW$ at 800 GeV is presented in figure 14. It shows the difference between generated and reconstructed photon energy in the jet. The distribution is well symmetric, it has been fitted with two gaussians, the narrow one has a mean of 0.23 GeV and a width of 7.01 GeV, the wide one, which corresponds to a third of the narrow, has a mean of -.02 GeV and a width of 18.5 GeV.

Even if the photon reconstruction appears in a rather good shape, a more complete reconstruction of the jets at high energy has to be done and is under way.

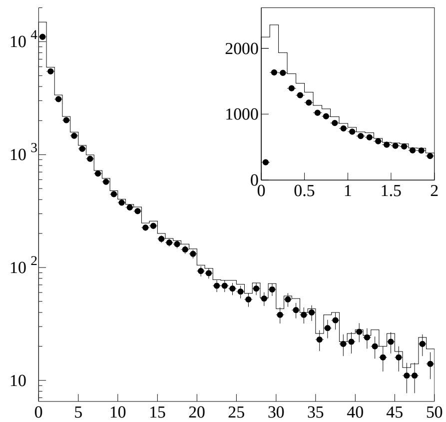



Figure 12. Energy distribution for generated photons and true photons reconstructed.

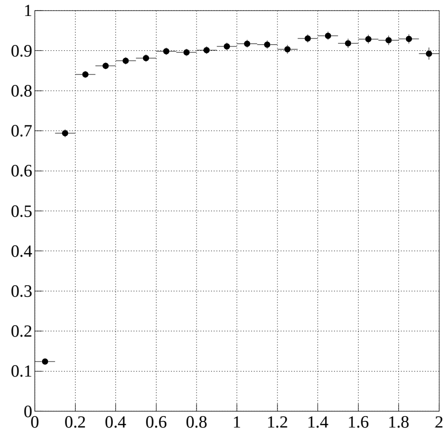



Figure 13. Photon efficiency at low energy.

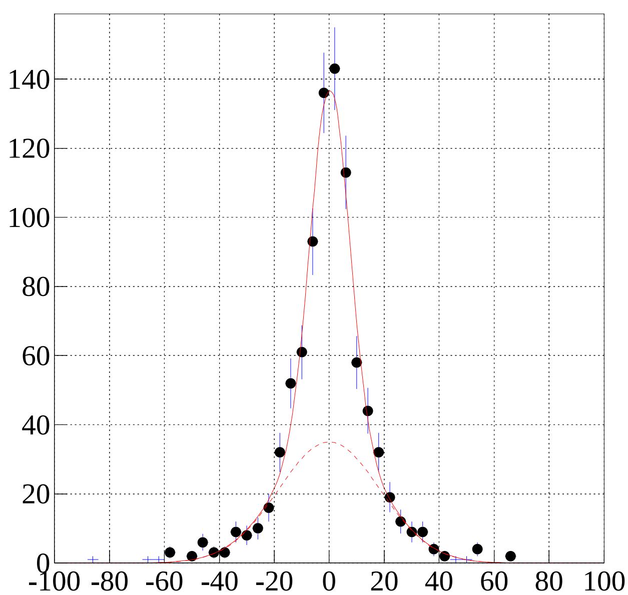
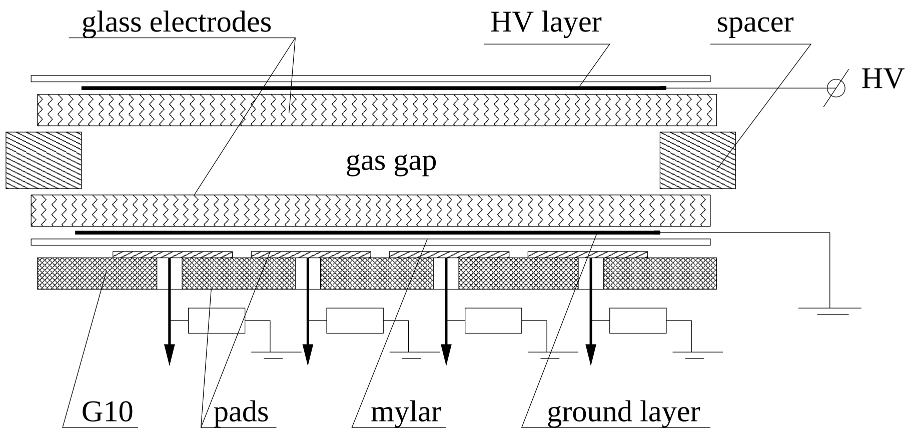



Figure 14. Energy resolution for the photonic contribution to jets.

## 4. Few more informations about the digital HCAL solution

The results presented above rely on the simulation of a very granular HCAL. Is there a technology for such a detector? We discuss here quickly a solution



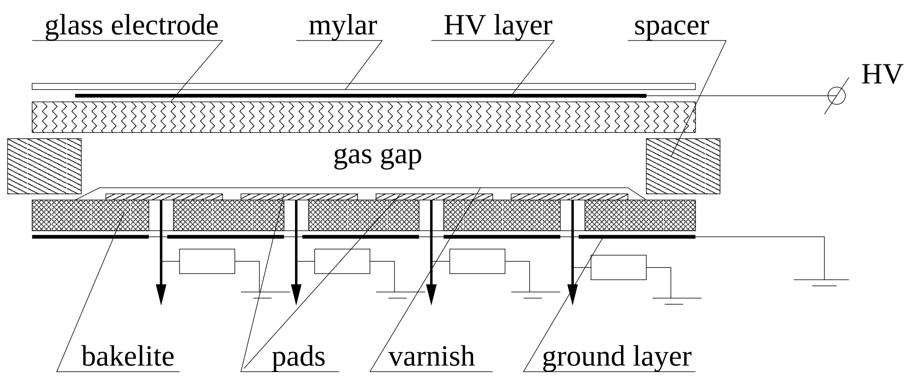




Figure 15. Scheme of a RPC with pads outside or inside the chamber.

under development.

The requirements for a sensitive detector are to be compact, efficient to mip, with a high output signal and cheap. A straight idea is to consider a gas detector, either a streamer or Geiger wire detector or RPC's. Currently the last solution is actively pursued in a subcollaboration of CALICE involving IHEP, Interphysica, LLR, MEPhI and Seoul university.

The figure 15 shows two designs for a glass RPC. In the first one, on top, the read out pads are outside the glass panels. To get a larger signal and to reduce cross-talk between adjacent pads a solution with pads inside is also considered, bottom. The gap is 1.2 mm, the glass plates are 1mm thick and the pad size is 1x1 cm$^2$. With a mixture of tetrafluoroethan, nitrogen and isobutane in the proportion 80/10/10 a signal of 3V is obtained on 50$\Omega$ and

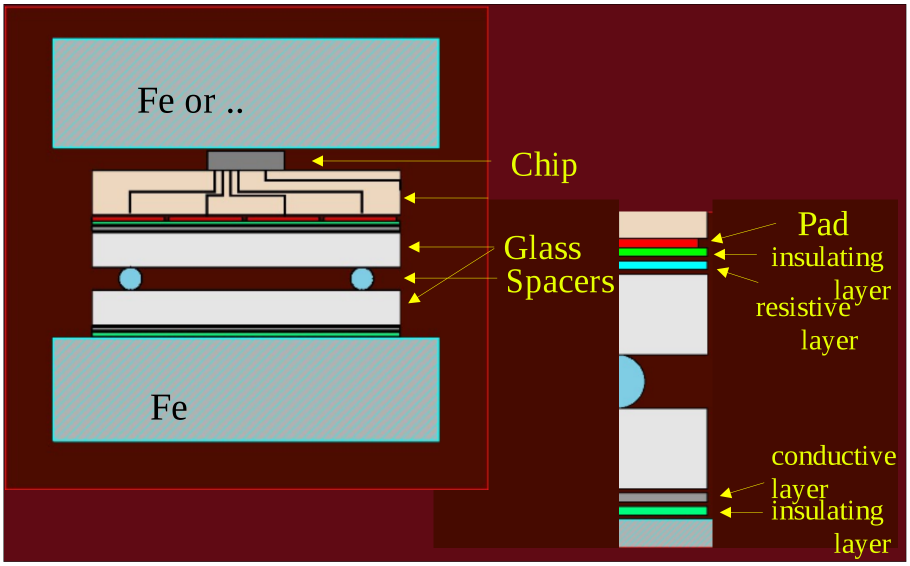



Figure 16. Scheme for implanting the read out directly on the RPC.

the efficiency to mip is better than 98%.

The figure 16 shows the structure of the HCAL gap. Between the two radiator layers made of stainless steel ot heavier material, a classical glass RPC is installed. The pads are put on a multilayer G10 board containing the connections of 64 pads to a chip seated on the board, as well as the power, command and read out lines.

Figure 17 shows then a possible read out scheme for a 64 channel chip followed by the drawing of a token ring reading the chips serially. The current idea is to have the 64 pad lines arriving in parallel to the chip. If one line at least is up, the 64 bits are recorded together with an identification of the bunch crossing time. Between trains, the chips memories are read one after another, the chip address being added. Remember that, if the number of channels is as large as 64 million channels, the occupancy of the cells is very low, typically a 20 GeV pion shower generates between one and two hundred hits.

## 5. Perspectives and conclusions

To extract the physics produced in an electron linear collider below 1 TeV, a measurement of the jet energies with a stochastic term at a level of 0.3 or below seems mandatory. Such a precision does not seem out of reach with an adequate calorimetric hardware and a proper software.

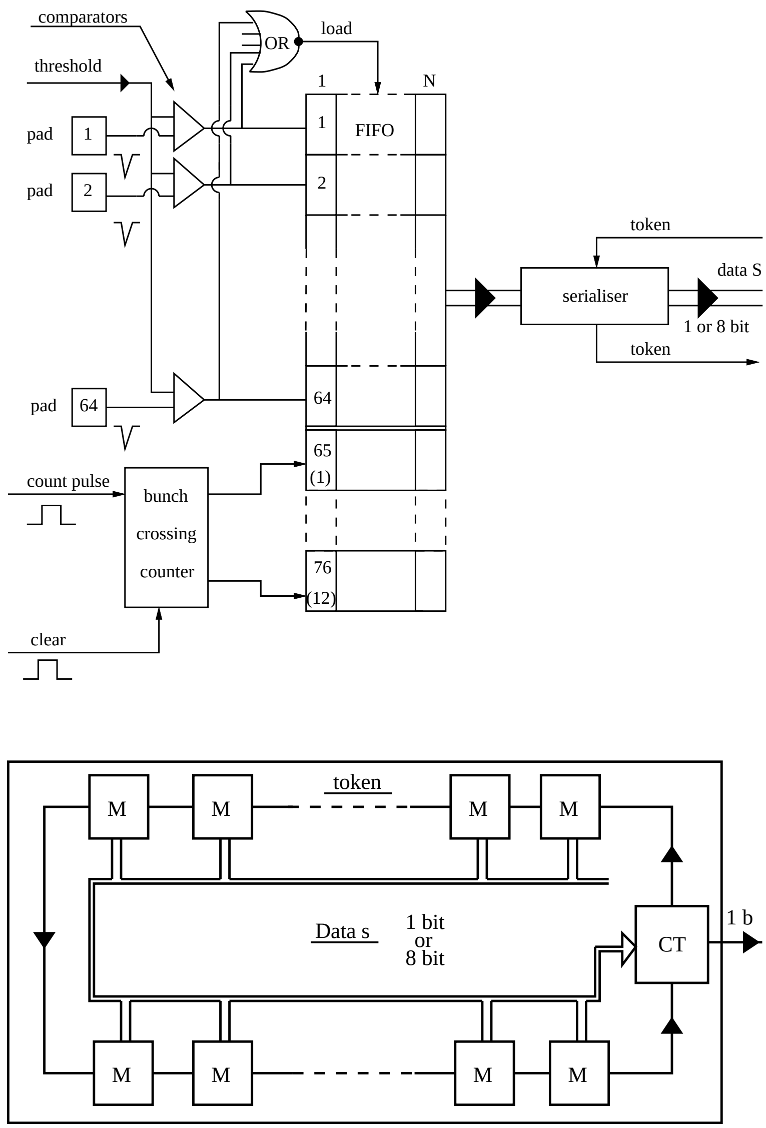



Figure 17. Scheme for a RPC digital front end chip (above) and its read out (bottom).

We have a roadmap with hardware developments and prototypes ( in beam in 2004) and with a lot of software imagination. If you like to play this game, join the worldwide effort of the CALICE collaboration.

http://polywww.in2p3.fr/tesla/calice.html